

# Microfabrication Techniques for Millimeter-Wave Vacuum Electronics

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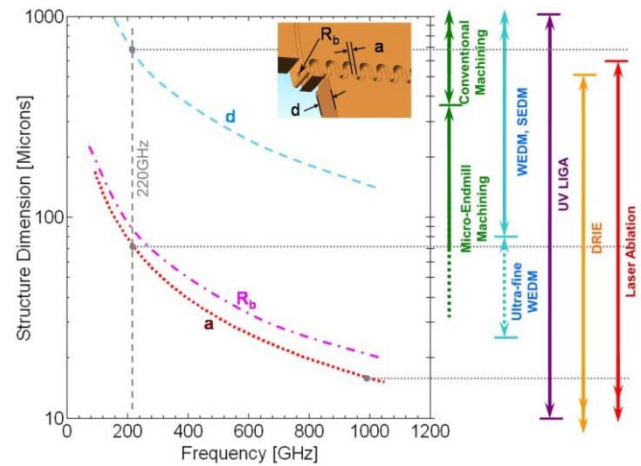
**Abstract:** The principal challenge for creating vacuum electron devices in the millimeter-wave (mmW) frequency range is accurate fabrication of slow-wave circuits and other electromagnetic features with tight tolerance. Ultraviolet Photolithography and Electroforming (UV-LIGA) techniques are presented that allow tight tolerance control for slow wave circuits for the mmW and sub-mmW bands. We show how these techniques were applied at the W- and G-bands.

**Keywords:** Photolithography; microfabrication; UV-LIGA; millimeter waves; vacuum electronics; traveling wave tube.

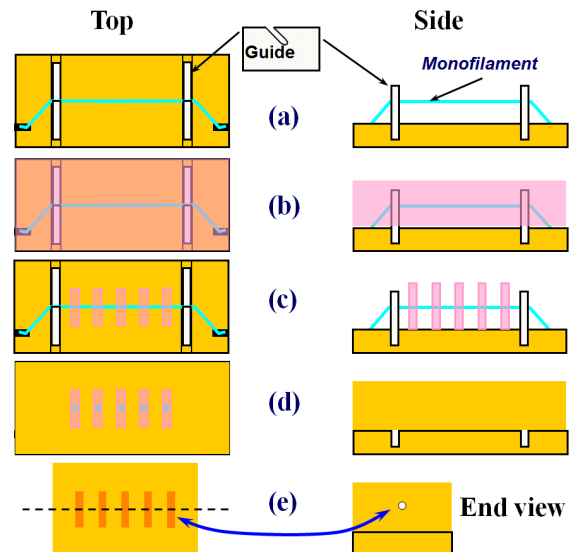
## Introduction

Copper is an important material for high-power millimeter-wave (mmW) vacuum electronic slow-wave structures (SWS) due to its high thermal and electrical conductivities, vacuum compatibility, and the fact that it is non-magnetic [1]. But traditional micro-scale fabrication techniques including Deep Reactive Ion Etching (DRIE) are implemented on materials such as silicon that do not have the thermal and electrical properties needed. In addition, many of the newest and most technologically advanced techniques focus on nano-scale fabrication and are incapable of fabricating features as large as on the scale of 10's or 100's of microns or have build volume limitations incompatible the needs of Slow Wave Structures (SWS).

Figure 1 compares the efficacy of several manufacturing techniques, both additive and subtractive. While 3D printing is a rapidly advancing technology, no techniques to date (to the authors' knowledge) have been able to manufacture fully dense, 3D-printed pure copper. But certain types of SWS circuits, such as folded waveguide, require only 2D manufacturing methods. Micro-endmilling is progressing, but is still very limited for high vertical aspect ratio (VAR) features. For a folded waveguide SWS, the VARs required can easily reach 10:1. WEDM must cut entirely through a workpiece and thus requires multiple brazes that negatively affect tolerance. Laser ablation is very difficult on copper due to its high thermal conductivity and high laser reflectivity. Therefore lithography and electroforming was chosen as a path forward. While X-ray lithography can produce much smaller and more accurate features, it is often cost prohibitive compared to UV-LIGA.



**Figure 1.** Diagram illustrating the limitations of certain fabrication technologies with respect to the structure dimensions versus frequency of a serpentine wave guide slow-wave circuit. WEDM/SEDM: Wire/Sinker Electrical Discharge Machining.



**Figure 2.** UV-LIGA process: (a) UV-transparent monofilament positioned above the substrate and (b) embedded in SU-8 photoresist [2]. (c) The patterned photoresist and monofilament is a quasi-3D mold for copper electroforming (d). (e) The completed all-copper circuit needs only a flat lid brazed on.

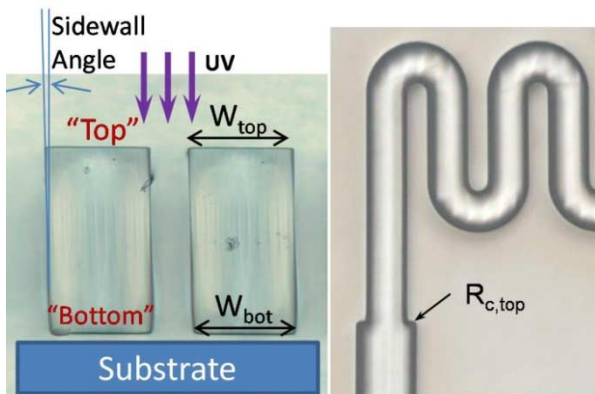
## UV-LIGA

Figure 2 illustrates a typical UV-LIGA process where a photoresist is patterned to make a mold. Copper is electroformed around the mold, and finally the mold is removed. We embed a UV-transparent monofilament in the photoresist in order to form the electron beam tunnel for the SWS [2]. We have used both a 365 nm UV flood source with a photomask and a Heidelberg muPG101 desktop laser pattern generator with a 375 nm laser for SU-8 activation. The laser system produces much sharper and more accurate features at the top surface, but defocuses as it passes a distance through the SU-8. Table 1 shows typical tolerances achieved with the laser system. The resolution is worse using the UV flood source because of inevitable gaps between the mask and SU-8, but the collimation is much better, so the resolution is the same at the top and bottom surfaces.

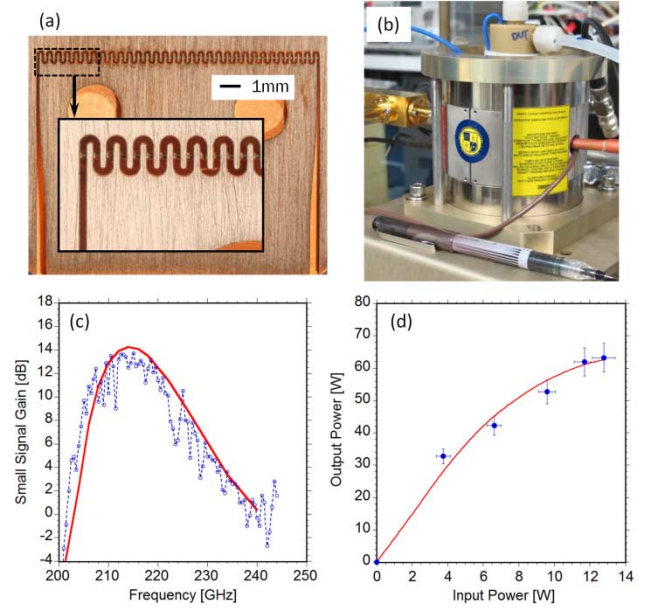
Copper electroforming is performed in a tank of sulfuric acid and copper sulfate using a current controlled triangle waveform with agitation [2]. The growth rate is about  $6 \mu\text{m hr}^{-1}$  at  $10 \text{ mA cm}^{-2}$ . After grinding to thickness and polishing with silicon-carbide and diamond pads, the SU-8 is completely removed using a Downstream Chemical Etching (DCE) process machine from Muegge, GmbH. A flat lid is brazed on to complete the circuit.

**Table 1.** Typical tolerances for the laser pattern generator. Many numbers quoted depend on the laser focus position.

SU-8 Depth:	100 $\mu\text{m}$	200 $\mu\text{m}$	300 $\mu\text{m}$
Laser spot size ( $\mu\text{m}$ )	3	3	3
Top Width error, $\nabla W_{\text{top}}$	-0/+2	-0/+4	-0/+5
Bottom Width error, $\nabla W_{\text{bot}}$	+1/+4	0/+4	-1/+5
Top Radius, $R_{\text{c,Top}}$	1-2	1-4	2-6
Bottom Radius, $R_{\text{c,Bot}}$	5-6	6-9	8-12
Sidewall Angle	0.3°	0.6°	0.8°



**Figure 3.** (Left) Side view of an SU-8 structure with definitions for Table 1. (Right) Top view of SU-8 structure.



**Figure 4.** (a) 220 GHz TWT circuit fabricated by UV-LIGA, (b) completed compact tube, (c) small signal gain, (d) power drive curve achieving 63 W output.

## Demonstration

A 220 GHz traveling wave tube (TWT) circuit was created using the UV-LIGA method with a photomask in two layers with the embedded polymer filament to create the shape of the beam tunnel. This tube demonstrated 63 W output power at 214.5 GHz with 13 W input power, 15 GHz bandwidth in the small signal regime, and a peak circuit gain of 14 dB [3]. Efforts are underway to create circuits at W-band [4] and G-Band for high gain TWTs.

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